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**ARES V AND FUTURE VERY LARGE LAUNCH VEHICLES TO ENABLE MAJOR
ASTRONOMICAL MISSIONS**

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ABSTRACT

The current NASA architecture intended to return humans to the lunar surface includes the Ares V cargo launch vehicle, which is planned to be available within a decade. The capabilities designed for Ares V would permit an 8.8-m diameter, 55 mT payload to be carried to Sun-Earth $L_{1,2}$ locations. That is, this vehicle could launch very large optical systems to achieve major scientific goals that would otherwise be very difficult. For example, an 8-m monolith UV/visual/IR telescope appears able to be launched to a Sun-Earth L_2 location. Even larger apertures that are deployed or assembled seem possible. Alternatively, multiple elements of a spatial array or two or three astronomical observatories might be launched simultaneously.

Over the years, scientists and engineers have been evaluating concepts for astronomical observatories that use future large launch vehicles. In this presentation, we report on results of a recent workshop held at NASA Ames Research Center that have improved understanding of the science goals that can be achieved using Ares V. While such a vehicle uniquely enables few of the observatory concepts considered at the workshop, most have a baseline mission that can be flown on existing or near-future vehicles. However, the performance of the Ares V permits design concepts (e.g., large monolithic mirrors) that reduce complexity and risk.

1. WORKSHOP BACKGROUND AND GOALS

On April 26th and 27th, 2008, NASA Ames Research Center, directed by Dr. Peter Worden, hosted a two-day workshop entitled “Astronomy Enabled by Ares V.” The primary goal of the workshop was to begin the process of bringing the Ares V designers together with senior representatives of the astronomical community to discuss the feasibility of using the Ares V cargo launch vehicle, a major element in NASA’s Constellation Program, to launch large observatories. This paper reports on the essential results and recommendations of the workshop. A complete report of the workshop has been produced by Langhoff, Lester, Thronson, and Correll (2008) [1].

All presentations and discussions at the workshop referred to the Ares V design concept at that time. The design and even the name “Ares V” could change in the future. Nevertheless, we believe this workshop opened up astronomical trade space for any future generation heavy-lift launcher.

Key questions at the workshop included:

- (1) Are there telescope concepts or missions capable of breakthrough science that are either enabled or significantly enhanced by the capabilities of an Ares V cargo launch vehicle?
- (2) What demands do large telescopes place on the payload environment of the Ares V, such as mass, volume, fairing shape, cleanliness, acoustics, etc.?
- (3) What technology and environmental issues need to be addressed to facilitate launching observatories on an Ares V?

- (4) Is there a trade-off between mass and complexity that could reduce launch risk and, thereby, the cost of building large telescopes?

The results of this workshop has been provided to the National Research Council’s *Science Opportunities Enabled by NASA’s Constellation System* study effort, which is currently underway.

2. WORKSHOP SUMMARY

The workshop began with an overview of the Constellation program and the role of future NASA launch vehicles. One of the essential ground rules of the workshop was that changes in the Ares V cargo launch vehicle cannot compromise its primary mission of transporting the Altair lander and supplies to the lunar surface.

The large lift mass capability of Ares V (approximately 55 metric tons to Sun-Earth $L_{1,2}$) and large fairing (8.8 meter interior diameter) opens up new telescope design possibilities that could significantly enhance the future scientific missions of many kinds. As it transpired, most of the observatory concepts that were discussed at the workshop are limited by volume, not mass, and many of the missions could take advantage of a “taller” fairing than the baseline design. The length of the Ares V fairing is ultimately constrained by the height of the Vehicle Assembly Building (VAB).

While an Ares V cargo launch vehicle uniquely enables a few of the telescope concepts considered at the workshop, most have a baseline mission that can be flown on existing or near-future heavy-lift launch vehicles. However, the large fairing and lift capabilities of the Ares V open up new design flexibility, for example large mono-

lithic mirrors of reduced complexity and have no risk of deployment. Such larger-aperture telescopes offer much higher sensitivity and spatial resolution than telescopes that can be launched with current launch vehicles. This is particularly important for studies of the early Universe and for imaging exosolar planetary systems.

While it is too early in the design cycle of the Ares V for a definitive understanding of its launch environment, designing to a launch environment comparable or better than the Shuttle was considered a good metric. Since the main engines can be throttled, it is expected that the acoustic and dynamic loads can be kept within acceptable limits.

One recurring theme that had not been included in the workshop agenda was the importance of on-orbit servicing of astronomical observatories. The recent success of the Defense Advanced Research Projects Agency's (DARPA) Orbital Express demonstrated that on-orbit servicing can be done autonomously if the telescopes are designed for standard servicing functions. For almost two decades, the Hubble Telescope servicing missions have dramatically increased the scientific value of the telescope by implementing improved instruments and detector technology. The Ares V cargo launch vehicle and other Constellation assets could enable servicing of satellites either with robots or with astronauts. It is precisely because Ares V and other future large vehicles can launch extremely large, capable, and expensive telescopes that on-orbit servicing to repair and upgrade those telescopes appears to add considerable value. This subject is further discussed in Section 3.5.1 and is recommended to be the subject of follow-on workshops.

The workshop clearly showed that the Ares V has considerable potential to do breakthrough astronomy. It is also likely that it could advance the Earth science and planetary science goals of NASA. A follow-on workshop on solar system science applications was held at NASA Ames August 17 and 18, 2008. The results of that workshop will be reported on separately.

3. WORKSHOP PRESENTATIONS AND DISCUSSION

3.1. The Ares V Cargo Launch Vehicle

The workshop began with an overview of the Constellation Program by Steve Cook, Ares Project Manager at NASA MSFC. The discussion here attempts to capture some of the key points made in his presentation, and to set the stage for the science cases that follow. More in-depth and authoritative accounts of the rapidly unfolding Constellation and Ares programs exist on the web, for example, at http://www.nasa.gov/mission_pages/constellation/ares/aresV.html. The key focus of the Constellation Program is to deliver both cargo and humans to the lunar surface by 2020. At the same time, it has been increasingly recognized that such transport systems can straightforwardly access other interesting destinations such as Geosynchronous Earth Orbit (GEO), the Sun-Earth and Earth-Moon Lagrange (libration) points, and some asteroids.

Key elements of the Ares V cargo launch vehicle were adopted for the workshop. The payload fairing is being designed to carry the Altair lunar lander. One of the primary focuses of the workshop was to determine what demands launching large astronomical observatories might place on the size of the fairing. There may be some design flexibility in the fairing as long as it carries

out its principal mission of transporting Altair to the lunar surface. Other elements of the Ares V presented at the workshop include the Earth Departure Stage (EDS), a loiter skirt, an interstage, and then the core stage powered by five Delta IV derived RS-68 LOX/LH2 engines and two solid rocket boosters. The Ares V presented at the workshop is being designed to use many of the major components being developed for the Ares I crew launch vehicle. For example, the first-stage 5-segment solid rocket boosters, the J-2X upper stage engine, and the instrument unit, will all have heritage on Ares I. This adaptation is intended to greatly reduce schedule and cost risks, as well as development and life-cycle costs.

3.2. Overview of Ares V Performance

Phil Sumrall, the NASA MSFC Advanced Planning Manager for the Ares Projects Office, gave a two-part presentation on Ares V, providing first a mission and vehicle overview, and then a description of performance. Again, we emphasize that this is a current snapshot of an on-going program. The Ares V cargo launch vehicle, which is primarily being designed to place large masses on the lunar surface, is intended to have greater payload capacity to low Earth orbit (LEO) (~140 metric tons (mT)) than any previous vehicle, including the Saturn V. The Orion crew exploration vehicle (CEV), which is launched separately on an Ares I crew launch vehicle, performs a rendezvous and docking with the EDS. Finally, the EDS trans-lunar injection (TLI) burn sends the Altair lunar lander/CEV on to the Moon. A loiter skirt, which is connected to the EDS, supports a four-day loiter period in LEO. Presumably, on an Ares V mission used to launch an observatory, this loiter skirt and loiter period would not be required, which would add further to the payload capacity.

Sumrall discussed in detail the design

concepts for all of the key elements of the Ares V including the EDS, the core stage, the notional instrument unit, the EDS J-2X engine, the SRBs, and the upgraded RS-68 engine. As all this information is available on-line

(http://www.nasa.gov/mission_pages/constellation/main/index.html) and not critical to how an Ares V could be used to launch large telescopes, we omit the details here. However, the element of the Ares V that seems most important for astronomical missions is the shape and interior dimension of the upper stage fairing. Sumrall presented a shroud shape trade study that they had done within the restriction of a 9.7-m barrel height. This barrel height is required to accommodate the current Altair lunar lander configuration. They considered many shapes, but selected the biconic shroud shown as their baseline. A critical dimension is the 8.8-m diameter interior of the barrel. The maximum length of the barrel is constrained to 18.7 m by the height of the Vehicle Assembly Building (VAB) at Kennedy Space Center (KSC). Increasing the barrel length to this maximum reduces the payload mass capability slightly. For example, the payload to Sun-Earth L_2 is reduced from 55.8 to 55.1 mT by using the extended fairing. For astronomical missions, the longer notional shroud was generally favored (see later discussion), because these missions are usually constrained by volume, not payload mass.

Preliminary analyses indicate that the payload environment (e.g., acoustic loads, vibration, cleanliness, etc.) should be comparable to other heavy launch vehicles and thus unlikely to negatively impact launching large telescopes. This is discussed in more detail for specific missions in the following sections.

3.2 Lessons from HST: Maximizing the

Value of Large Investments

Frank Cepollina (NASA GSFC) presented a paper discussing the lessons that have been learned from the Hubble Space Telescope (HST) servicing missions. [2] He began with a quote from NASA Administrator, Michael Griffin, who observed, "It is dumb to launch complicated, expensive telescopes into space that cannot be serviced." With the opportunity that Ares V and other future large systems presents to launch very large and potentially expensive telescopes, it is especially useful to consider on-orbit servicing as a means of expanding their scientific productivity.

The thesis of Cepollina's talk was that HST servicing missions have dramatically increased the scientific value of the telescope. Periodic changes in instruments to focus on new scientific questions, and the implementation of new instrument detector technology, result in a continuing rejuvenation of the scientific performance of this popular mission, and an enhanced pace of innovation and discovery. Cepollina described the history of on-orbit servicing missions beginning with the Solar Maximum Repair Mission. To date, there have been nine servicing missions to a variety of LEO satellites, which have shown that a satellite's design (e.g., standardized modularity) is the single most significant aspect of cost apart from launch costs. Of these nine there have been four servicing missions to HST, each time resulting in new scientific discoveries and an explosion of scientific papers. The SM4 servicing mission planned for late 2008 will add the Cosmic Origins Spectrograph and Wide Field Camera 3, again extending the science capabilities of the telescope. To date, there have been over 6000 refereed papers generated from HST data. With the completion of SM4, Hubble will again be at

the apex of discovery potential. The importance of on-orbit servicing in extending the lifetime and science capabilities of a telescope could not have been made more dramatically, according to Cepollina.

Looking toward the future, Cepollina outlined a concept for a piloted Orion servicing vehicle. He discussed the possibility of a servicing arm attached to Orion and controlled telerobotically by onboard astronauts. His mission concept was to replace an instrument of a large telescope at its operational location at Sun-Earth L_2 point or, alternatively, at the more accessible Earth-Moon L_1 jobsite [Ref. 3 and this conference] using an augmented Orion and Lunar Surface Access Module (LSAM). Cepollina reported on a study that compared costs of a series of expendable new telescopes versus a regularly serviceable telescope, which indicated that the servicing scenario was less costly overall. He ended by emphasizing that the time is now to start studying how elements of the Constellation program such as the Orion crew exploration vehicle could contribute to the major science goals by extending human and robotic servicing missions to the next generation telescopes; that is, if we can do servicing missions with the Shuttle, why not with Orion?

3.4. Telescope Concepts/Missions

The Ares V cargo launch vehicle could be a significant enhancement for astronomical observations by allowing for much larger telescopes, which in turn enables much fainter objects to be studied. In this section, we summarize the presentations on seven astronomical concepts that are either enabled by or significantly enhanced by the availability of an Ares V cargo launch vehicle.

3.4.1 Emerging Pathways for the Single-Aperture Far-Infrared Telescope (SAFIR) with an Ares V.

Dan Lester (University of Texas) discussed how an Ares V cargo launch vehicle could enhance the Single Aperture Far Infrared Telescope (SAFIR) concept. The large interior diameter of the Ares V shroud allows for a large single-substrate (monolith) primary mirror diameter of approximately 8 m. SAFIR is designed to obtain spectra in the far infrared (FIR) ($\sim 20\text{--}300\ \mu\text{m}$) using high-performance focal plane FIR sensors. The entire telescope is cooled to less than 10 K by both passive and active means. SAFIR will explore the FIR universe with higher sensitivity and spatial resolution than previously achieved, providing new insights into the cosmic history of star formation and nucleosynthesis. [4, 5]

With an Ares V, the single-substrate 8-m mirror could be launched with no deployment mechanisms required. This could significantly reduce complexity, risk, deployment design, and integration and testing, which translates into reduced cost. Since SAFIR is diffraction limited at $20\ \mu\text{m}$, the optics will be lighter than, for example, the James Webb Space Telescope (JWST). The launch mass is only 10 mT or $\sim 20\%$ of the launch capacity of Ares V for a mission to Sun-Earth L_2 . This would allow significant augmentations to the observatory such as more/larger instruments, as well as an enhanced spacecraft. Simple scaling of the SAFIR baseline concept, but with a JWST-like deployable primary mirror, would allow a $\sim 20\text{-m}$ diameter telescope with 10 times the sensitivity and 2–3 times the spatial resolution to be accommodated by an Ares V cargo launch vehicle.

A key message of Lester's presentation was the importance of servicing the spacecraft. For this to be feasible, the spacecraft would have to be modular to facilitate the replacement of the focal plane science instruments, spacecraft systems, and the solar shield. Instrument upgrades are particularly important in the FIR, for which detector sensitivity and array sizes are undergoing rapid improvement. Lester described a servicing concept where the telescope is brought back from its optimal operating location at Sun-Earth (SE) L_2 to Earth-Moon (EM) L_1 , which is much more convenient for human travel. Transit from SE L_2 to EM L_1 requires only a few tens of meters/sec ΔV [3].

3.4.2. ATLAST: The Roadmap to an 8-m to 16-m UV/Optical Space Telescope

Marc Postman (Space Telescope Science Institute) described a concept for both an 8-m and 16-m UV/Optical Space Telescope that could be deployed from an Ares V. The Advanced Technology Large-Aperture Space Telescope (ATLAST) would have unprecedented sensitivity and angular resolution in the optical region. It could investigate a wide range of important astronomical issues, such as how the present Universe formed, how galaxies form, and how planetary systems form from circumstellar disks. [6] In conjunction with a separately launched external occulter or a high-performance coronagraph to block the light from the central star, it would be able to characterize the atmospheres of exosolar planets. The 16-m ATLAST, in particular, would be able to obtain spectra of the atmospheres of Earth-like planets in the habitable zone of thousands of candidate stars.

As in the previous talk by Dan Lester, Postman also discussed the tradeoff between mass and mission complexity. Reducing

complexity reduces risk and cost, thus an Ares V could reduce the overall cost of the mission by allowing a less-complex observatory. For example, the Ares V enables a fully deployed 8-m or folded segmented 15- to 20-m telescope in a single launch. However, this would require the “tall” option Ares V fairing. Without an Ares V, multiple launches, complex folded optics, and/or on-orbit assembly would be the only alternatives for deploying a telescope larger than about 7 m in diameter. Postman ended his presentation by discussing the technology developments that need to be made prior to launch. Designing the mission to enable on-orbit servicing was also identified as a high priority.

3.4.3 Stellar Imager (SI): Viewing the UV/Optical Universe in High Definition

Ken Carpenter (NASA GSFC) discussed Stellar Imager, which is a space-based UV/Optical interferometer with over 200 times the resolution of the Hubble Space Telescope. With its combination of high angular resolution, dynamic imaging, and spectral energy resolution, it is capable of performing breakthrough science in the UV/Optical spectral region. Science goals include an improved understanding of solar and stellar magnetic activity and understanding accretion mechanisms in sources ranging from planet-forming systems to black holes. The sub-milli-arcsecond angular resolution enables the study of dynamical structure and physical processes in currently unresolved sources such as active galactic nuclei (AGN), supernovae, planetary nebulae, and interacting binary stars. SI is also capable of imaging transits of exosolar planets across their stellar disks. It is a candidate large-class strategic mission for the mid-2020s.

The Stellar Imager concept calls for a space-based UV/Optical Fizeau interferometer with a variable maximum baseline of 100 up to 1000 m. The interferometer is proposed to be located near Sun-Earth L_2 to enable precision formation flying. The baseline concept consists of 30 1-m mirror elements focusing light into a single beam-combining hub. The baseline concept can be launched on a Delta-IV Heavy. The Ares V cargo launch vehicle, with its much larger fairing volume, enables larger mirror elements, which dramatically improves sensitivity and reduces observation times. This increases the science productivity, especially for fainter extragalactic sources and for astroseismic observations. In addition to larger mirrors, a single launch of an Ares V could also include more than one hub and a reference metrology/pointing control spacecraft. This would greatly increase the operational efficiency and robustness of the mission. The value of in-situ servicing, such as refueling and repairing or replacing damaged hardware, was also emphasized for this mission.

3.4.4 Generation-X: A Mission Enabled by Ares V

Roger Brissenden (Smithsonian Astrophysical Observatory) discussed an X-ray telescope concept known as Generation-X [7]. The science goals include studying the early universe where the first black holes, stars, and galaxies formed, as well as their evolution with cosmic time. The telescope would also provide new insights into the physics of matter in extreme environments. Key parameters in the baseline concept are that the effective area at 1 keV be 50 m^2 and the angular resolution be 0.1 arcsec. To meet the effective area requirement of 50 m^2 requires about 104 m^2 of glass area. This, in turn, requires thin mirrors ($\sim 0.1\text{--}0.2 \text{ mm}$) to meet mirror

spacing and launch mass requirements, although the mass is less of an issue with the Ares V launch payload capacity. Since the requirements on effective area imply a 12-m diameter mirror, this would require either multiple launches and assembly, multiple satellites, or a single monolithic mirror that could only be launched on an Ares V.

The original mission concept using a Delta-IV Heavy called for six identical 8-m diameter telescopes, each carried as six segments to fit in the fairing. The Ares V enables a simplified and more cost-effective mission concept. The baseline concept calls for a partially filled 16-m diameter mirror, which folds to fit within a 10-m fairing. The X-ray telescope is delivered directly to Sun-Earth L₂, and the estimated spacecraft mass of 22 mT is far less than the 55 mT Ares V capability to this location. Since the telescope is volume-limited, not mass-limited, the mass margin enables design freedom for the optics, structure, supporting electronics, and the science instruments. The ideal situation would be to have a fully filled ~12-m monolithic mirror that would need no deployment, thereby reducing cost and risk.

Brissenden ended his presentation by discussing some of the technology developments that would be needed to enable the Generation-X mission. Significant improvements to the mirror figure control are required to achieve the high-angular resolution mission parameter.

3.4.5 Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) Spectrometer Enabled by Ares V

Stephen Rinehart (NASA GSFC) discussed the SPECS far-infrared (FIR) interferometry mission [8,9] This system consists of 4-m collector telescopes and a Michelson beam

combiner with a one-kilometer baseline constrained by tethers. The interferometer is designed to achieve an angular resolution of 50 milli-arcsec over a wavelength range of 40–640 μm , simultaneously obtaining spectral and spatial information using a double-Fourier technique. This would allow spatial resolution in the FIR that is comparable to HST at optical wavelengths. Science priorities include studies of the first stars (whose light is redshifted into the FIR), galaxy evolution, star formation, and planetary and debris disks. The spectrometer is designed with sufficient sensitivity to map high-redshift extra-galactic sources.

The SPECS mission could be launched on a Delta 4 Heavy, but the larger fairing of the Ares V could be significantly enhancing. This would allow different packaging options, which would in turn lead to a much simpler deployment scheme. In addition, the Delta 4 Heavy launch limits SPECS to a pair of 4-m monolithic mirror telescopes. While this would achieve the SPECS stated science goals, an Ares V would allow for both more and/or larger collector telescopes. Other potential benefits would be to use the larger launch payload of an Ares V to carry more propellant for a longer mission lifetime and to perhaps add a servicing spacecraft that could do both refueling and repair and replacement. DARPA's Orbital Express mission demonstrated such a capability in 2007.

3.4.6. The Dark Ages Lunar Interferometer

Joseph Lazio (NRL) gave a presentation on the Dark Ages Lunar Interferometer (DALI) concept, a telescope designed to conduct cosmological observations of the so-called "Dark Ages" of the early universe and, potentially, of the Epoch of Reionization. The Ares V is likely to be required for the

DALI concept, both because the extreme faintness of the desired signal requires substantial collecting area (and, hence, mass), and because the desired site for the telescope is the far side (i.e., anti-Earthward side) of the Moon.

The ground state of the hydrogen atom has the famous 21-cm hyperfine transition. After recombination, about a half-million years after the Big Bang, the dominant component of the intergalactic medium (IGM) is atomic hydrogen, and the predicted temperature of the gas eventually drops below that of the cosmic microwave background (CMB). Even well into the Epoch of Reionization, the IGM remains dominated by neutral hydrogen, although a more complicated temperature evolution is predicted as the first stars and black holes form and heat and ionize the IGM. Depending upon the redshift, the hyperfine transition should be seen in either absorption or emission against the CMB, and would serve as a cosmological probe in much the same way that the CMB itself has been over the past four decades. Importantly, the redshifted 21-cm transition may offer the opportunity to follow the evolution of the Universe during this crucial epoch. Secondary science includes studying the magnetospheric emission from exosolar planets and heliophysics.

The baseline DALI concept calls for a large number (hundreds) of antenna “stations,” with each station consisting of 100 antennas. The nominal location is the Tsiolkovsky crater. The stations would be deployed with robotic rovers, and signals from the stations would be transmitted via laser links to a correlator. The Moon’s far side may be the only place in the inner solar system where these observations can be carried out, due to strong terrestrial (human-generated) emissions in the radio that are effectively

blocked in this location. The current antenna concept consists of dipoles deposited on polyimide film. Each rover would unroll the polyimide film rolls for its station, then remain in place to serve as a “transmission hub,” beaming the signals from its station to a central processing facility. Elements of the Constellation architecture, both the Ares V and the cargo version of the Altair lander, present an attractive means of deploying the large launch mass of the telescope, which is dominated by the antennas and rovers.

3.4.7. Starshades in the Ares V

Tupper Hyde (NASA GSFC) reviewed the next generation missions intended to characterize exosolar planets using a starshade, which Ares V might enable. He discussed the sequence of missions to characterize exosolar planets beginning with the baseline New Worlds Observer Spectroscopy mission to characterize planets at low spectral resolution. This mission could be carried out with current heavy-lift launch vehicles. The next most advanced mission is Life Finder that would carry out medium resolution spectroscopy ($R \sim 10000$) of the atmospheres of exosolar planets. This would require a large 8- to 16-m telescope in conjunction with a starshade. Here an Ares V cargo launch vehicle would be enhancing, but not absolutely essential. The next most ambitious mission called Planet Imager, which requires multiple telescopes to carry out large-baseline imaging interferometry plus starshades, could only be carried out with an Ares V or an equivalently capable vehicle.

In all of these mission concepts, the starshade is used as an external occulter to block the light from the star. The telescope needs to be large enough to collect enough light from the planet and needs to be far enough away from the starshade to have a

suitably small inner working angle. Low-resolution spectroscopy ($R \sim 100$) would be sufficient to distinguish terrestrial from Jovian atmospheres, for example. At this resolution it should be possible to detect oceans and continents using photometry. Hyde showed that resolution, and thus mirror size, is critical. He then described the New Worlds Imager concept in the context of the Ares V, where much larger mirrors would be enabled. Since Ares V enables large volume and mass, its launches loaded with multiple telescopes and starshades would enable the following: (1) A single 8-m telescope and two starshades; (2) two 4-m telescopes and four starshades; or (3) an imaging interferometer: combiner fed by two or three collector telescopes with starshades. Like many of the astronomy missions, a fairing taller than the current Ares V baseline is preferred.

3.4.8. Panel Discussion on Strategic Trades and Questions

The workshop began on the second day with a panel discussion entitled “strategic trades and questions.” The seven astronomers who presented telescope concepts on the first day were panelists. This was an opportunity for the scientists to discuss with the Ares designers what were the drivers in the payload environment for their mission concept. It should be emphasized that many of these missions have Evolved Expendable Launch Vehicle (EELV) baseline options. For example, the SAFIR baseline is a large single-substrate primary mirror baseline of approximately 8 m. This larger mirror could be launched without deployment mechanisms on an Ares V, thereby reducing complexity, risk, and probably cost.

Most of the payloads are limited by volume, not mass. As discussed previously, a longer shroud is very advantageous for some of

these concepts (ATLAST, SI, and Starshade), while the Gen-X and SPECS payloads would benefit from a larger-diameter shroud. In most cases, the expected launch environment for the Ares V (acoustics, cleanliness, and power) is adequate for these astronomy missions. However, neither the mission concepts nor the payload environment have yet been defined adequately to be definitive.

One of the discussion topics in the panel discussion was the availability of the Ares V. Many felt that for Ares V to be viewed as a viable resource for non-human spaceflight space science missions, it needs to devote at least one launch vehicle to such a mission (including Earth science, planetary science, heliophysics, and astrophysics) every several years or so. The issue of availability of Ares V to the science communities, its cost, and the impact on its primary mission of returning humans to the Moon were considered critical topics for future discussion.

3.5 Technology Challenges

3.5.1 Future Space Robotics and Large Optical Systems

A strong theme in the workshop was the attractiveness of servicing the large astronomical observatories that large launch vehicles make possible. Our servicing experience to date is primarily with the Hubble servicing missions that have been performed by astronauts. However, in part because we would like to service observatories further from Earth, e.g., out at SE L_2 or EM L_1 , robotic servicing missions become an attractive alternative to human servicing.

The feasibility of autonomous, robotic on-orbit servicing was clearly demonstrated by

Tracey Espero (Boeing), who discussed the very successful DARPA Orbital Express mission and the future of space robotics and large optical systems. Orbital Express (OE) demonstrated the technical feasibility, operational utility, and cost effectiveness of autonomous techniques for on-orbit satellite servicing. Specific objectives of OE were to demonstrate on-orbit propellant and component transfer and autonomous rendezvous, proximity operations and capture. The overarching OE objective was to demonstrate the technical feasibility of autonomous on-orbit satellite servicing.

Orbital Express consisted of two separate spacecraft, the Autonomous Space Transfer and Robotic Orbiter (ASTRO) servicing spacecraft and the Next Generation Satellite/Commodity Spacecraft (NEXTSat) serviced (or client) spacecraft. ASTRO used a hydrazine monopropellant reaction control system for six degree-of-freedom control. It had a number of active servicing functions such as rendezvous and proximity operations sensors, a robotic arm, and an active capture system. NEXTSat had attitude determination and control, but no maneuver capability. It had standard servicing interfaces for all orbital replacement units (ORUs). The importance of modularity and standard interfaces were stressed.

The ASTRO servicing spacecraft successfully demonstrated propellant transfer to NEXTSat with varying degrees of autonomy. It also performed battery and computer transfers flawlessly. The advanced robotic arm on ASTRO was used to drive a camera at its tip to aid in capturing NEXTSat. The importance of having cameras on the servicing spacecraft was stressed. The OE mission accomplished many firsts, such as the fully autonomous propellant and ORU transfers, free-flyer capture, and long range (> 400 km)

rendezvous. This suggests that it would be possible to service large astronomical observatories in space.

3.5.2. Future Deployment systems and Very Large Fairings

Chuck Lillie (Northrop Grumman Space Technology) presented concepts for the future of deployment systems and very large fairings. While Ares V will permit very large telescopes to be launched without such deployment systems, even larger telescopes now considered completely unrealizable can be considered with such a vehicle. He began by discussing the James Webb Space Telescope (JWST), as it represents the current state of the art in large space observatories. He noted that technology improvements have changed the cost-to-aperture scaling “relationship” that is often quoted, namely that cost is commonly taken to be proportional to aperture to the 2.5 power. He predicted that further technology development plus infrastructure changes (such as the Ares V) will improve the ability to produce cost-effective large observatories. This optimistic view is dependent on a continued technology investment program in advanced optics technologies such as replication, improved wavefront sensing, and control technologies, as well as advanced deployment and assembly technologies.

He discussed the possibility of a 16.8-m version of JWST that could be stowed in the Ares V notional fairing (i.e., a fairing that is longer than the current baseline) with a “chord-fold” deployment system. A preliminary analysis indicates that this augmented 16.8-m version of JWST would fall within the Ares V lift capacity. He also discussed a 21-m diameter stacked-hex deployment that deploys seven 8-m point-to-point hexagonal mirror segments, and a 24-m diameter fan-fold deployment telescope

that contained 12 pie-shaped segments. All of these concepts require the taller Ares V notional fairing. Although these deployment concepts may add complexity, he demonstrated that complex deployments could be done with a high probability of success. The 24-m fan fold concept has 426 m² collecting area compared with 27 m² for the 6.6-m JWST.

Lillie noted that the standard Ares V fairing severely constrains payload packaging aperture size. For example, it would constrain the chord fold packing to 12-m versus 16.8-m diameter for the notional fairing. The notional fairing's mass, volume, cylinder height is well suited for optical payloads and is consistent with payload accommodations on current launch vehicles.

Lillie concluded by noting that the Ares V will enable a new generation of very large space observatories. To achieve this goal, however, we must have a sustained development program in deployment technologies, among other areas, although NASA has reduced its investments in future technologies of all kinds.

3.5.3. Libration-Point and Lunar-Swingby Trajectories

As we are interested in putting large observatories into libration point orbits, it is of interest to discuss whether humans can get there to do servicing. Bobby Williams (JPL) presented a paper on libration (or Lagrange) point and lunar swingby trajectories. These trajectories enable space telescope servicing either by transporting a repair team to, for example, SE L₂ or by returning the telescope to an elliptic Earth orbit. In presenting this paper, Williams made the assumptions that large space telescopes at SE L₂ will require servicing, repair, or other upgrade, that human space

exploration will continue, and that the Constellation vehicles Orion and Ares I will be developed.

Williams presented an Interplanetary Transfer Vehicle (ITV) mission scenario for telescope servicing at the SE L₂ libration point. A Deep-Space Shuttle (DSS) services the telescope that is in a halo orbit around SE L₂ for a period of five days, and then exits L₂. The crew then returns to Earth in an Orion-style capsule. The trip time is about 35 days. An important point is that the delta-V requirements for lunar, geosynchronous, and SE L₂ are similar. He recommended using a low-cost, low-risk incremental approach to developing capabilities. First, develop the DSS, which has transit times of 2 days to geosynchronous orbit, 10 days to lunar orbit, and 30 days to SE L₂. This would provide the capability to service space telescopes that are in halo orbits around SE L₂.

In key respects, a more attractive scenario would have the telescopes travel from SE L₂ to an EM L₁ "job site" and service them there with robots and/or astronauts [3]. This jobsite is 84% of the way to the Moon and, while it is not an optimal site for telescope operation, is easily accessible to the lunar-capable Constellation architecture, offering relatively quick return to the Earth or refuge to the lunar surface. This option requires very little delta-V to move the telescope, and is highly advantageous in terms of mission length for astronauts. In this scenario, the telescope, rather than the astronauts, has to travel for a month or more. Finally, Williams recommended developing the ITV for missions to NEAs and beyond.

3.6 Breakout Sessions

3.6.1. Breakout #1: What Breakthrough Astronomy Might be Enabled by Ares V?

Telescopes flown on Ares V will undoubtedly have scientific capabilities significantly in excess of those of current space observatories. Those capabilities may lead to breakthrough results that are unattainable from current facilities. Over the next ten to twenty years, though, it may be possible to obtain some of those capabilities through other means, such as assembly of large-aperture observatories in space or by flying formations of spacecraft from multiple smaller launchers. This breakout group considered potential breakthrough astronomical investigations foreseen for observatories flown on Ares V and tried to discern which would be uniquely enabled by this new launch vehicle.

The group concluded that there was no astronomy that was uniquely enabled by an Ares V, but observations that might be feasible through other means (for example, with multiple launches on smaller vehicles, and in-space assembly), become more practical with an Ares V. For example, payloads may be cheaper per unit volume and mass, or less complex with less deployment risk. Also, an Ares V may enable astronaut servicing missions of telescopes at remote locations, if this proves to be an optimal strategy. The group also felt that the astronomical community needed more time and resources to reevaluate their long-term goals in light of new capabilities afforded by an Ares V heavy-lift vehicle.

3.6.2. Payload Development: Technology and Environmental Issues

While the Ares V presents a great opportunity for the astronomy community, there are technology and launch environment issues that should be considered to allow full use of the heavy lift and large volume available with Ares V. A

long list of potential technologies was discussed, and the areas that were considered the highest priority were narrowed down so that the Ares V team can focus on enabling design features.

The Ares V baseline design is already very good for astronomy missions. Specifically, the vehicle's mass and fairing volume capabilities are enabling technologies for new science missions. The ability to support the payloads with power and data/health monitoring meets expected requirements. The areas the team felt were enabling and needed further study are described below.

Fairing Volume: The volume of the fairing was considered to be the highest-priority design issue that could enable large breakthrough astronomy missions. Increased volume can be achieved by increasing either the diameter or height of the fairing or both. The Ares V designers felt that increasing the diameter past the current baseline of 10 m would be both costly and difficult, because the body of the entire rocket is 10 m in diameter, and designing a hammer-head payload fairing on such a large vehicle presents significant challenges. The designers noted that while the Ares V fairing is designed to support the Altair lunar lander, a modular fairing design could probably be extended in height up to what is allowed within the Vehicle Assembly Building (VAB). To go higher would involve costly modification for the VAB. The Ares V designers agreed to study modular designs that would support taller fairings.

Launch environment: The team felt the launch environment was crucial to sensitive astronomy facilities. However, the large payload capacity of the Ares V allows flexibility to make the telescope more rugged.

Static loads: Since large astronomy observatories such as HST have been launched with the Shuttle, the group felt that the Ares V should not provide a launch environment that would be more stressful than a Shuttle payload could endure.

Dynamic and acoustic loads: The goal for Ares V should be as good or better than the current launch environment on other heavy-launch vehicles such as the Shuttle, Atlas, Ariane, and Delta rockets. The Ares V designers will use the metric of “as good as the Shuttle” as a point of departure on trade studies.

Cleanliness: Astronomy missions have extremely sensitive instruments and cleanliness is an important issue. The fairing of the Ares V should support a continuous N₂ purge during integration and pre-launch activities at the pad. The Ares V should also use the Shuttle cleanliness requirements as a point of departure on trade studies.

Mission Capability: The destination for many astronomy missions is the SE L₂ location, as it provides a better thermal environment, more stable power, and better observation opportunities. Unlike human missions to the Moon, in which Earth-orbit rendezvous is part of the mission plan, it is desirable to launch observatories to SE L₂ on a direct mission profile without going into Earth orbit. This would have the added advantage of avoiding the need for the loiter collar, thereby resulting in savings in both cost and mass.

One major exception presented at the meeting was the DALI concept that uses one or more Ares V vehicles to deploy a very large number of dipole antennas on the dark (at radio wavelengths) lunar farside. In addition, the cargo version of the Altair system was identified in the baseline

concept for this mission for carrying the observatory elements to the lunar surface.

Support Servicing, Maintenance, and Upgradeability: It also appeared desirable for the Constellation system to be capable of enabling both human and robotic servicing missions to telescopes, for example, at SE L₂ or at an Earth-Moon libration point “jobsite.” [Ref. 3 and this meeting] Servicing astronomy facilities in space greatly increases the science output, which has been demonstrated by the Hubble Space Telescope.

Support for secondary payloads important (to take advantage of excess mass): The group felt that since most astronomy payloads did not require the full mass payload afforded by an Ares V launch, secondary payloads or missions of opportunity should be considered to fill any excess volume. To take full advantage of this approach, the group recommended that the Ares V team design a standard payload adapter similar to the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) ring.

3.6.3. Is There Value in Simplicity?

Overview: A major concern in considering the use of heavy-lift launch vehicles is whether or not the very large payloads they would deploy are affordable in their own right. Current heavy-lift launch vehicles have deployed NASA complex space science missions costing in the \$5 B range. If we were to increase the size and mass of such missions by a factor of five times, would the science budget be able to afford missions that cost up to \$20 B or more? It is conventional wisdom that a major predictor of mission cost is mass. However, mission complexity is also a major driver of mission cost, and may even be the dominant factor.

The same cost models show that historically, missions of the same mass, but of average difficulty, would cost only about \$10 B, or about half the price. This leads mission designers to consider what could be gained by using the increased mass and volume of the Ares V launch vehicle to reduce complexity and, hence, cost.

Some questions to consider: Complexity allows principal investigators and mission designers to gain performance from a volume- and mass-constrained launch system. Thus, the workshop recommended exploring how Ares V permits 1) enhanced mission performance; 2) reduced risk; 3) more optimized schedules; and 4) reduced cost. To do so, the scientists and engineers will need to consider how the additional mass and volume can lead to simple and rugged designs. This will also lead to a re-thinking of the ground processing and testing infrastructure for simple and rugged, but also larger and heavier spacecraft, apertures, and components. Along with this, designers will have to consider if modular approaches to systems design and the potential use of on-orbit assembly and servicing. While modularity and servicing often entail additional features in the design, these are not always of increased complexity.

Mass and Volume – Simplicity trades: Typically, the highest priority of telescope design is the size of the primary aperture of the system. Large apertures are needed for cutting edge science, and current approaches such as the James Webb Space Telescope rely on a fairly complex segmented optic system that must be carefully deployed and stowed, protected from the harsh launch environment, and then deployed in space for operations. To deploy even larger apertures in space, the Ares V would allow for a monolithic optic. Reduced need for stowing and deployment is estimated to produce a

30% savings in overall mission development cost, although with the loss of a light-collecting aperture. Thus, the space program could take advantage of the lower cost of primary mirrors that are produced for ground-based telescopes with relatively minor modification, and often even simplifications to their manufacturing process, given that the large optic deployed in space is less susceptible to concerns of gravity offloading and sag in the optic. A preliminary, nominal design for a 6-m integrated telescope and spacecraft (but not including instruments) was presented at the workshop with a cost of \$1.2 B and mass of 35 mT.

In addition, modularity needs to be considered in these designs. Modularity can already provide cost-saving benefits in that subsystems and modules can be independently tested before integration. Additionally, if problems come up during integrated testing, the modules are easily disassembled for repair or rework, where in tightly integrated designs, the disassembly and subsequent reassembly can be very complicated, risky, and expensive. For larger and heavier spacecraft designs considered for Ares V deployment, the need for handling fixtures and test facilities will almost require that a modular approach be used.

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